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Research article

Diagnostic errors in clinical FDG-PET/CT

Norah A. Alotaibi, Derya Yakar, Andor W.J.M. Glaudemans, Thomas C. Kwee *

Medical Imaging Center, Department of Radiology, Nuclear Medicine and Molecular Imaging, University of Groningen, University Medical Center Groningen, the Netherlands

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ABSTRACT

Purpose: To determine the frequency, types, and determinants of diagnostic errors in clinical FDG-PET/CT, based on addenda to the original report.

Materials and Methods: This retrospective study included 4,099 consecutive clinical FDG-PET/CT scans with corresponding reports that were made at a tertiary care center in an 18-month period. FDG-PET/CT reports were scrutinized for the presence of an addendum enclosing a diagnostic error.

Results: 90 of 4,099 FDG-PET/CT reports (2.2%) contained an addendum enclosing a diagnostic error. The distribution of perceptual and cognitive errors among these 90 diagnostic errors was 54 (60.0%)/36 (40.0%). On multivariate logistic regression analysis, only low-dose FDG-PET/CT combined with concomitantly acquired and interpreted full-dose contrast-enhanced CT remained as significantly and independently associated with the presence of a diagnostic error, relative to low-dose FDG-PET/CT without concomitantly acquired and interpreted full-dose contrast-enhanced CT (odds ratio: 2.79 [95% confidence interval: 1.61-4.85], $P < 0.001$). Patient age, gender, hospital status, indication for FDG-PET/CT scanning, single vs. double reading (i.e. two medical imaging specialists), reader experience, and reading by a nuclear medicine physician only vs. reading by both a nuclear medicine physician and a radiologist, were not significantly and independently associated with the presence of a diagnostic error.

Conclusion: Diagnostic errors in clinical FDG-PET/CT based on addenda to the original report are relatively infrequent, though certainly non-negligible. Perceptual errors are slightly more frequent than cognitive errors. The availability of a concomitantly acquired and interpreted full-dose contrast-enhanced CT seems to increase diagnostic error rate. These data can be used for quality improvement and benchmarking purposes.

1. Introduction

Integrated positron emission tomography (PET)/computed tomography (CT) with the radiotracer ^{18}F-fluoro-2-deoxy-D-glucose (FDG) is an established imaging modality for the evaluation of a wide range of human diseases [1]. Accurate interpretation of FDG-PET/CT scans is crucial for correct patient management in terms of further diagnostic testing, treatment planning, and prognostic purposes. However, interpretation of medical imaging examinations is a complex process that is error prone [2].

Diagnostic errors can be broadly divided into perceptual errors (i.e. detection errors) and cognitive (interpretive) errors (i.e. decision errors in the perception of an abnormality) [2]. It has been reported that, with estimates of average diagnostic error rates ranging from 3% to 5%, there are approximately 40 million diagnostic errors involving imaging annually worldwide [3]. These diagnostic errors may not only harm the patient, but are also responsible for a considerable amount of unnecessary healthcare costs due to wasteful medical spending, and are a major cause of malpractice lawsuits against medical professionals [3]. If a diagnostic error is made, it is common practice to create an addendum to correct or expand on the original radiology report [4]. As such, addenda provide a valuable source to investigate errors in the interpretation of imaging studies [5].

Currently, there is a lack of literature on diagnostic errors in clinical FDG-PET/CT. Analysis of diagnostic errors in FDG-PET/CT and the circumstances under which they occur, may provide strategies for error

Abbreviations: CT, computed tomography; EANM, European Association of Nuclear Medicine; FDG, ^{18}F-fluoro-2-deoxy-D-glucose; PET, positron emission tomography; SPSS, statistical package for the social sciences.

* Corresponding author at: Department of Radiology, Nuclear Medicine and Molecular Imaging, University Medical Center Groningen, University of Groningen, Hanzeplein 1, P.O. Box 30.001, 9700 RB Groningen, the Netherlands.

E-mail address: thomaskwee@gmail.com (T.C. Kwee).

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reduction, and thereby improve patient care [2,3]. It can be hypothesized that certain patient variables (age, gender, in- or outpatient status, indication for FDG-PET/CT scanning), FDG-PET/CT scan acquisition method (low-dose FDG-PET/CT with or without concomitant full-dose contrast-enhanced CT), and FDG-PET/CT interpretation circumstances (single vs. double reading, reader experience, and reading by a nuclear medicine physician only vs. reading by both a nuclear medicine physician and a radiologist) may have an effect on diagnostic error rate.

The purpose of this study was to determine the frequency, types, and determinants of diagnostic errors in clinical FDG-PET/CT, based on addenda to the original reports.

Table 1
Patient, FDG-PET/CT acquisition, and FDG-PET/CT interpretation characteristics belonging to the 4,099 FDG-PET/CT scans that were included in this study.

Variable	No.[a]
Patient age (years)	57.9 ± 17.0
Patient gender (M/F)	
Male	1,838 (44.8%)
Female	2,261 (55.2%)
Hospital status	
Inpatient	564 (13.8%)
Outpatient	3,535 (86.2%)
Clinical indication for FDG-PET/CT	
Oncological	3,401 (83.0%)
Infection	291 (7.1%)
Inflammation	216 (5.3%)
Other	191 (4.7%)
FDG-PET/CT scan range	
Mid-thigh to cranial vertex	3,588 (87.5%)
Feet to cranial vertex	511 (12.5%)
Concomitant full-dose contrast-enhanced CT	
Yes[b]	2,133 (52.%)
No	1,966 (48.0%)
No. of readers per FDG-PET/CT scan[c]	
One	2,073 (50.6%)
Two	2,026 (49.4%)
Experience of first reader (years)[c,d]	8.13 ± 6.8
Experience of second reader (years)[c,d]	7.4 ± 5.9
Reader of FDG-PET/CT scan	
Nuclear medicine physician only	2,006 (60.4%)
Nuclear medicine physician and radiologist	1,313 (39.6%)
Presence of an addendum	
Yes	123 (3%)
No	3,976 (97%)
Time between the authorization of the original report and the addendum (days)	6 (2-14)
Presence of an addendum enclosing a diagnostic error	
Yes	90 (73.2%)
No	33 (26.8%)
Person who made the addendum	
Person who made the addendum was the same as the one who made the original report	61 (67.8%)
Person who made the addendum was not the same as the one who made the original report	29 (32.3%)
Time between the authorization of the original report and the addendum enclosing a diagnostic error (days)	6.5 (2-13)

Notes:
[a] Data are presented as No. (%), median (interquartile range), or mean ± SD.
[b] Full-dose contrast-enhanced CT was made of the following body regions: chest (n = 674), chest-abdomen (n = 589), neck-chest-abdomen (n = 517), neck-chest (n = 118), abdomen (n = 91), neck (n = 75), heart (n = 59), abdomen-legs (n = 7), neck-abdomen (n = 2), neck-chest-abdomen-legs (n = 1).
[c] Only medical imaging specialists (radiologists or nuclear medicine physicians) were counted.
[d] Readers' experience after completion of residency.

Table 2
Anatomic locations of all perceptual and cognitive errors.

Perceptual errors (n = 54)	Cognitive errors (n = 36)
Lymph nodes (n = 12)	Bowel (n = 3)
Vascular (n = 6)	Lung (n = 3)
Bone (n = 5)	Lymph nodes (n = 3)
Bowel (n = 3)	Subcutaneous tissue (n = 3)
Brain (n = 3)	Thyroid (n = 3)
Liver (n = 3)	Lung and lymph nodes (n = 2)
Spine (n = 3)	Oropharynx (n = 2)
Kidney (n = 2)	Stomach (n = 2)
Lung (n = 2)	Bone (n = 1)
Thyroid (n = 2)	Brain (n = 1)
Uterus (n = 2)	Breast (n = 1)
Anatomic location not specifiable (n = 2)	Esophagus (n = 1)
Abdominal wall (n = 1)	Heart (n = 1)
Bone and bowel (n = 1)	Liver (n = 1)
Bone and lymph nodes (n = 1)	Lung and lymph nodes (n = 1)
Brain and kidney (n = 1)	Mediastinum (n = 1)
Breast (n = 1)	Muscle and skin (n = 1)
Heart (n = 1)	Pancreas (n = 1)
Skin (n = 1)	Skin (n = 1)
Spleen (n = 1)	Spleen and lymph nodes (n = 1)
Urinary bladder (n = 1)	Subcutaneous tissue, lymph nodes and bone (n = 1)
	Uterus (n = 1)
	Anatomic location not specifiable (n = 1)

2. Materials and Methods

2.1. Study design

This study was performed at the University Medical Center Groningen, which is a tertiary care center that provides healthcare services to over 2 million inhabitants in the north-east of the Netherlands. The local institutional review board approved this retrospective study, and the requirement for informed consent was waived. All consecutive FDG-PET/CT scans that were performed between April 2016 and November 2017, were potentially eligible for inclusion. FDG-PET/CT scans were included if they involved mid-thigh to cranial vertex or feet to cranial vertex acquisitions, and if they were interpreted and reported by nuclear medicine physicians and/or radiologists as part of standard clinical care. FDG-PET/CT scans were excluded if they only involved specific body regions (e.g. brain, heart, or extremities), or if a clinical FDG-PET report was lacking (this may have been the case if the FDG-PET/CT scan was acquired at the request of another institution, or if the FDG-PET/CT scan was performed for research purposes).

2.2. FDG-PET/CT acquisition

FDG-PET/CT scans were acquired according to the European Association of Nuclear Medicine (EANM) procedure guidelines for tumor imaging [6], using integrated PET/CT systems (Biograph 40 or 64 mCT PET/CT, Siemens Healthineers, Erlangen, Germany). All patients fasted for at least 6 hours before 3 MBq/kg FDG was administered intravenously. Sixty minutes later, PET scanning was performed from either mid-thigh to cranial vertex or feet to cranial vertex, depending on the clinical indication of the scan. Low-dose (100 kV and 30 mAs) unenhanced CT scanning was performed for attenuation correction and anatomic mapping. Concomitant full-dose (constant tube potential of 100-120 kV with automatic tube current modulation in the z-direction) contrast-enhanced CT was performed in a subset of patients, depending on the clinical indication, directly after low-dose FDG-PET/CT using the same PET/CT system.

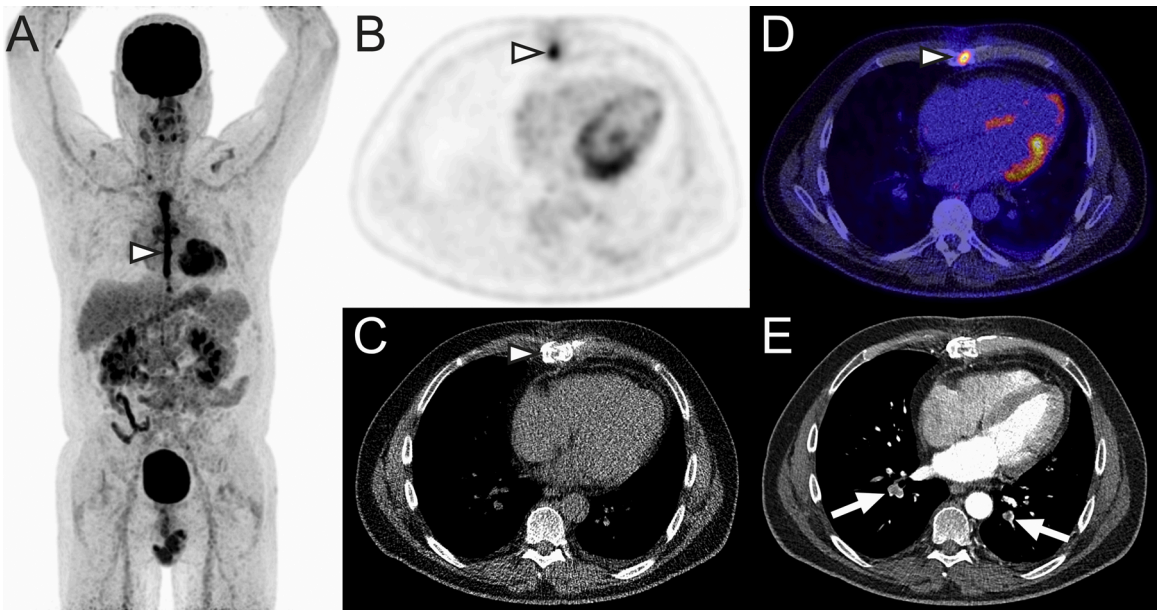

Fig. 1. A 55-year-old man with a history of coronary artery bypass surgery and recent endoscopic mucosal resection of an esophageal cancer. Low-dose FDG-PET/CT and concomitant full-dose contrast-enhanced CT were performed for staging purposes. Coronal maximum intensity projection FDG-PET (A), axial FDG-PET (B), axial low-dose CT (C), axial fused FDG-PET/CT (D), and axial full-dose contrast-enhanced CT (E) are demonstrated. Low-dose PET/CT showed physiologically increased FDG uptake at the sternotomy site (A-D, arrowheads), but otherwise no signs of metastatic disease. Contrast-enhanced CT showed emboli in both lower lobes (E, arrows), which were not visible on low-dose FDG-PET/CT. These pulmonary emboli were not described in the original report. This perceptual error was corrected with an addendum five days after authorization of the original report.

2.3. FDG-PET/CT interpretation

All low-dose FDG-PET/CT scans were interpreted by nuclear medicine physicians. All full-dose contrast-enhanced CT scans were interpreted by either radiologists or nuclear medicine physicians with national board certification in diagnostic CT interpretation (the latter group also interpreted the low-dose FDG-PET/CT scans by themselves). Low-dose FDG-PET/CT and full-dose contrast-enhanced CT were first reviewed separately, potential discrepancies were then discussed to reach consensus, and the findings of both modalities were finally integrated into one single report, in case two readers were involved. Low-dose FDG-PET/CT was always interpreted before full-dose contrast-enhanced CT, and the low-dose FDG-PET/CT scan and the corresponding preliminary report were available for review to the full-dose contrast-enhanced CT reader. Dedicated software (Syngo.via, Siemens Healthineers, Erlangen, Germany) was used for FDG-PET/CT interpretation, which allowed for side-by-side display of (low-dose and full-dose contrast-enhanced) CT, FDG-PET, and fused FDG-PET and (low-dose and full-dose contrast-enhanced) CT datasets. Addenda, if present, could have been made by either the same nuclear medicine physician or radiologist who created the original report, or a different one who was not involved in the original reading of the FDG-PET/CT scan.

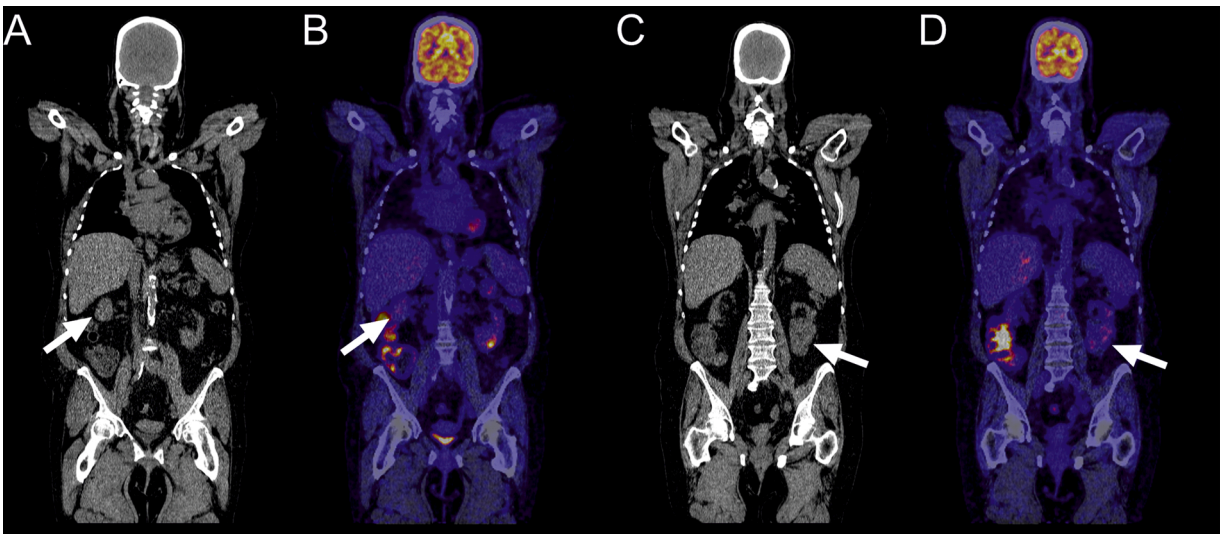

Fig. 2. A 59-year-old woman with fever of unknown origin. Low-dose FDG-PET/CT was performed to search for an infectious focus. Coronal low-dose CT (A, C) with corresponding coronal fused FDG-PET/CT (B, D) slices at two different levels are demonstrated. No infectious focus was found at FDG-PET/CT. Although both kidneys contained masses with low FDG avidity (A-D, arrows), they were not described in the original report. These masses proved to be clear cell renal cell carcinomas on follow-up. This perceptual error was corrected with an addendum 14 days after authorization of the original report.

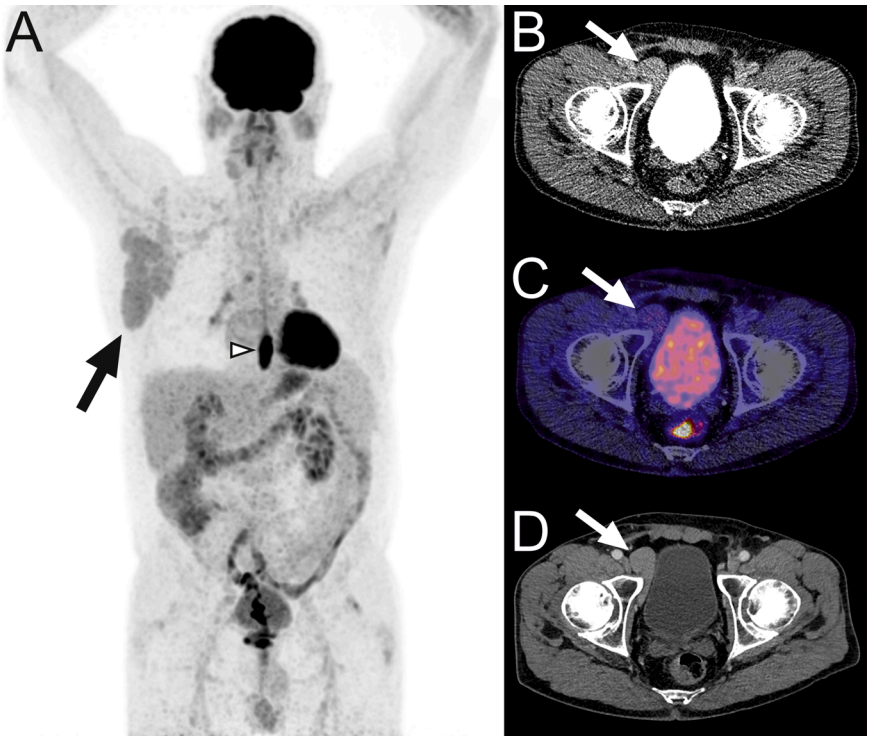

Fig. 3. A 69-year-old man with a history of chronic lymphocytic leukemia and palpable lymphomas in the right axilla. Low-dose FDG-PET/CT and concomitant full-dose contrast-enhanced CT were performed for staging purposes. Coronal maximum intensity projection FDG-PET (A), axial low-dose CT (B), axial fused FDG-PET/CT (C), and axial full-dose contrast-enhanced CT (E) are demonstrated. FDG-PET showed right axillary lymphomas with low FDG-avidity (A, arrow) and focal high FDG uptake in the distal esophagus (A, arrowhead), the latter suspicious for esophageal cancer. Although right para-iliac non-FDG-avid lymphomas were also visible (B-D, arrows), they were not described in the original report. This perceptual error was corrected with an addendum 22 days after authorization of the original report.

2.4. Data extraction

A research fellow (N.A.A.) manually scrutinized all FDG-PET reports performed between April 2016 and November 2017, and applied the previously mentioned in- and exclusion criteria. For all FDG-PET/CT reports that were included, the following variables were extracted: patient age and gender, hospital status (in- or outpatient), indication for FDG-PET/CT scanning (oncology, infection, inflammation, or other),

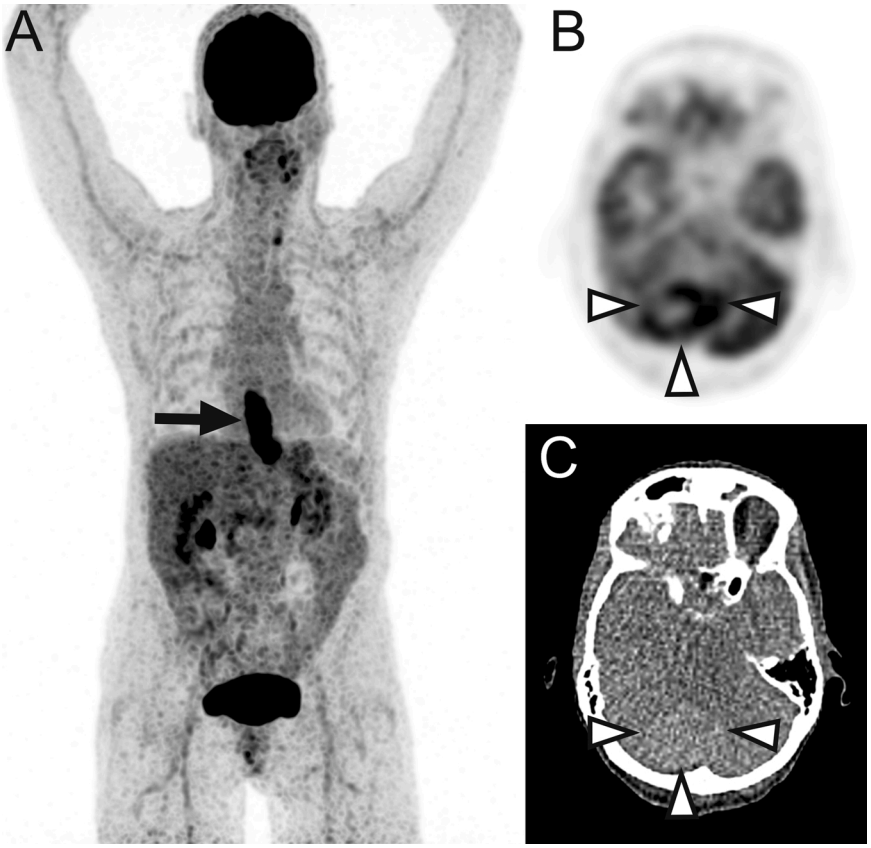

Fig. 4. A 62-year-old woman who had undergone neoadjuvant chemoradiation therapy for esophageal cancer. Low-dose FDG-PET/CT was performed for restaging purposes. Coronal maximum intensity projection FDG-PET (A), axial FDG-PET (B), and axial low-dose CT (C) are demonstrated. FDG-PET showed high FDG uptake at the location of the primary tumor (A, arrow) that had decreased compared to baseline FDG-PET (not shown). Although a mass with peripheral high FDG uptake was present in the right cerebellar hemisphere (B and C, arrowheads), this was not described in the original report. Follow-up confirmed metastatic disease. This perceptual error was corrected with an addendum 7 days after authorization of the original report.

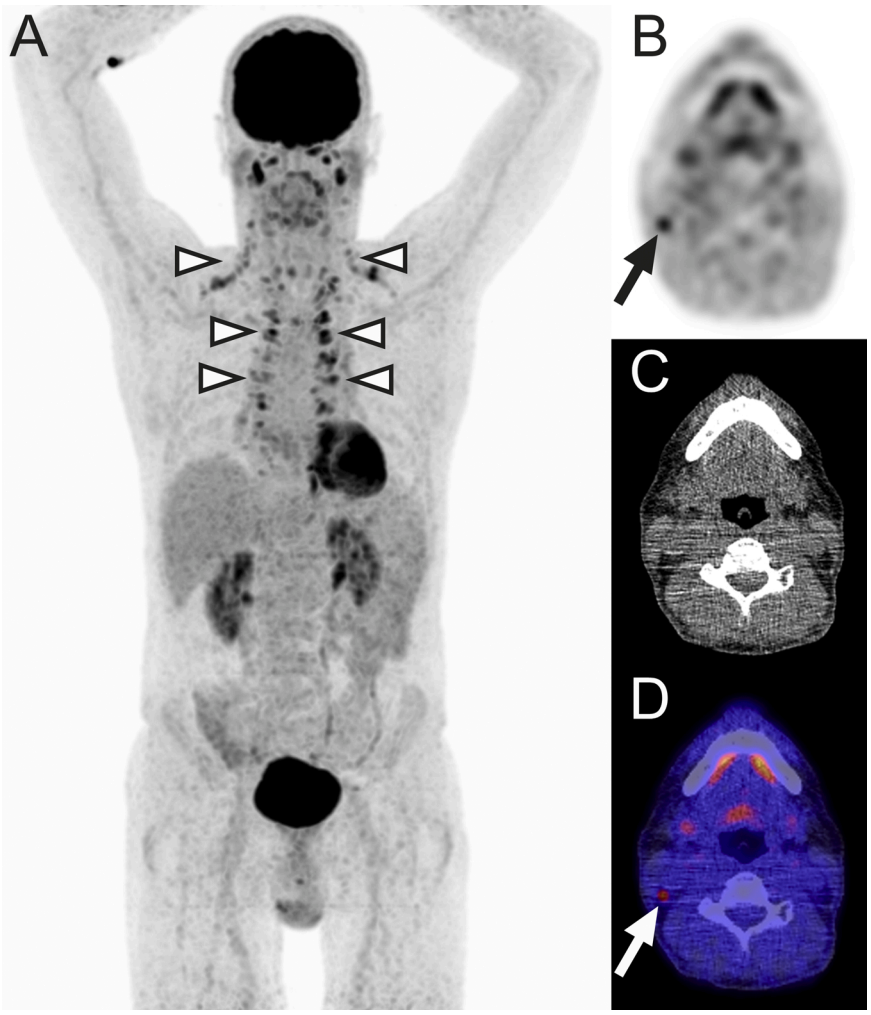

Fig. 5. A 59-year-old man who had received chemoradiation therapy for right-sided tonsillar cancer. Low-dose FDG-PET/CT was performed for staging purposes. Coronal maximum intensity projection FDG-PET (A), axial FDG-PET (B), axial low-dose CT (C), and axial fused FDG-PET/CT (D) are demonstrated. FDG-PET showed physiological FDG-avid brown fat in the bilateral cervical and paravertebral regions (A, arrowheads). Furthermore, an FDG-avid focus in the right side of the neck (B and D, arrows) was described as a possible lymph node metastasis in the original report. However, CT image at the same level (C) showed the FDG-avid focus in the right side of the neck to be localized in fatty tissue, and not in a lymph node. Therefore, it most likely also represented physiological FDG-avid brown fat. This cognitive error was corrected with an addendum two days after authorization of the original report.

FDG-PET/CT scan range (mid-thigh to cranial vertex or feet to cranial vertex), presence of absence of concomitantly acquired full-dose contrast-enhanced CT that was interpreted together with low-dose FDG-PET/CT, number and function (nuclear medicine physician or radiologist) of FDG-PET/CT readers, readers' experience after completion of residency, presence or absence of an addendum, and time between authorization of the original report and the addendum. If an addendum was present, it was classified as either due to diagnostic error or not related to diagnostic error (e.g. addenda with a correction of typographic errors or addenda with purely research-related assessments). Note that addenda with purely research-related assessments refer to addenda appended to clinical reports and that contain information that is used for research purposes only. E.g. an oncological FDG-PET/CT scan with a clinical report and an addendum in which additional measurements are documented for a certain study. Diagnostic errors were subsequently classified as either perceptual or cognitive [2].

2.5. Statistical analysis

The frequency of diagnostic errors enclosed in all addenda as a proportion of the total amount of FDG-PET/CT reports was calculated, along with 95% confidence intervals (CIs). Proportions of perceptual and cognitive errors were also calculated. Logistic regression analyses were performed to determine the association between the previously mentioned patient, FDG-PET/CT acquisition, and FDG-PET/CT interpretation variables with the presence of a diagnostic error. Variables with a *P*-value <0.10 on univariate logistic regression analysis were selected for subsequent multivariate logistic regression analysis. Variables with a *P*-value <0.05 on multivariate logistic regression analysis were considered to be significantly and independently associated with the presence of a diagnostic error. Statistical analyses were executed using the IBM Statistical Package for the Social Sciences (SPSS), version 25 (IBM SPSS, Armonk, NY, USA).

3. Results

3.1. FDG-PET/CT scans and reports

Between April 2016 and November 2017, 6,500 FDG-PET/CT scans were acquired. Of these 6,500 FDG-PET/CT scans, 1,789 were excluded because they only involved specific body regions (brain [n = 1,763], heart [n = 12], extremities [n = 14]), and 612 were excluded because a corresponding report was lacking. Thus, a total of 4,099 FDG-PET/CT scans with corresponding reports were included. Patient, FDG-PET/CT acquisition, and FDG-PET/CT interpretation characteristics belonging to the 4,099 FDG-PET/CT scans that were included in this study are displayed in Table 1.

3.2. Frequency and types of diagnostic errors

123 of 4,099 FDG-PET/CT reports contained an addendum, of which 90 enclosed a diagnostic error. Consequently, the diagnostic error frequency was 2.2% (95% CI: 1.8-2.7%). The distribution of perceptual and cognitive errors among these 90 diagnostic errors was 54 (60.0%)/36

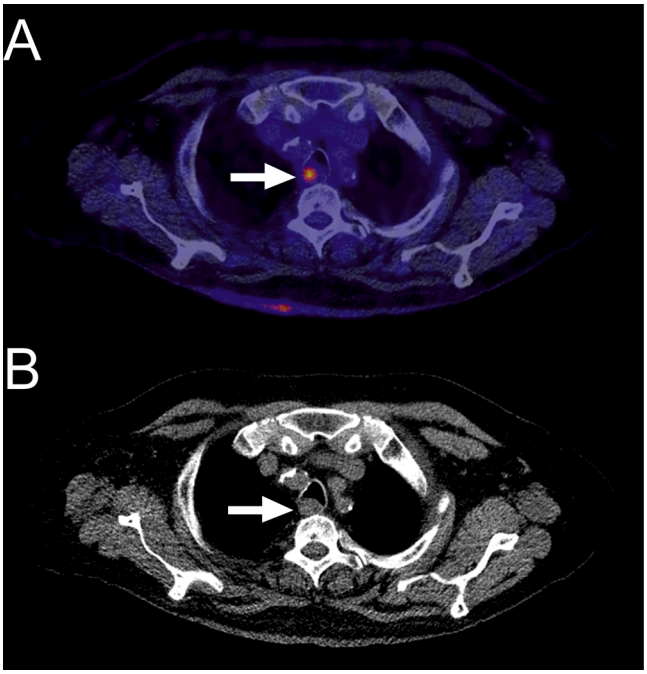

Fig. 6. A 71-year-old man with a history of liver transplantation and recent episodes of epilepsy with abnormalities in the left occipital lobe on CT (not shown). Low-dose FDG-PET/CT was performed to evaluate for post-transplant lymphoproliferative disorder. FDG-PET/CT showed pathologic FDG uptake in the left occipital lobe (not shown). Axial fused FDG-PET/CT (A) and low-dose CT (B) are demonstrated. FDG-PET showed focal high FDG uptake in the upper esophagus (A, arrow) with focal wall thickening on low-dose CT (B, arrow), which was interpreted to be most likely of physiological nature in the original report. However, this lesion proved to be esophageal cancer on follow-up. This cognitive error was corrected with an addendum 15 days after authorization of the original report.

(40.0%). The anatomic locations of all perceptual and cognitive errors are displayed in Table 2. Case examples of perceptual errors are shown in Figs. 1–4, and case examples of cognitive errors are shown in Figs. 5–8.

3.3. Determinants of diagnostic errors

On univariate logistic regression analysis, low-dose FDG-PET/CT scans with concomitantly acquired and interpreted full-dose contrast-enhanced CT, more frequently suffered from diagnostic errors than those without ($P < 0.001$). In addition, FDG-PET/CT scans read by a nuclear medicine physician only, more frequently suffered from diagnostic errors than those read by both a nuclear medicine physician and a radiologist ($P = 0.06$). All other variables (patient age, gender, and hospital status, indication for FDG-PET/CT scanning, single vs. double reading (i.e. two medical imaging specialists), and reader experience) did not reach *P*-values less than 0.10 on univariate logistic regression analysis (Table 2). On multivariate logistic regression analysis, only low-dose FDG-PET/CT combined with concomitantly acquired and interpreted full-dose contrast-enhanced CT remained as significantly and independently associated with the presence of a diagnostic error, relative to low-dose FDG-PET/CT without concomitantly acquired and interpreted full-dose contrast-enhanced CT (odds ratio of 2.79 [95% confidence interval: 1.61-4.85], $P < 0.001$) (Table 3).

3.4. Post-hoc analysis

From our preplanned analysis as executed in the previous section, it emerged that a higher error rate exists when a diagnostic-quality CT scan is available. We speculated that this is due to either the added

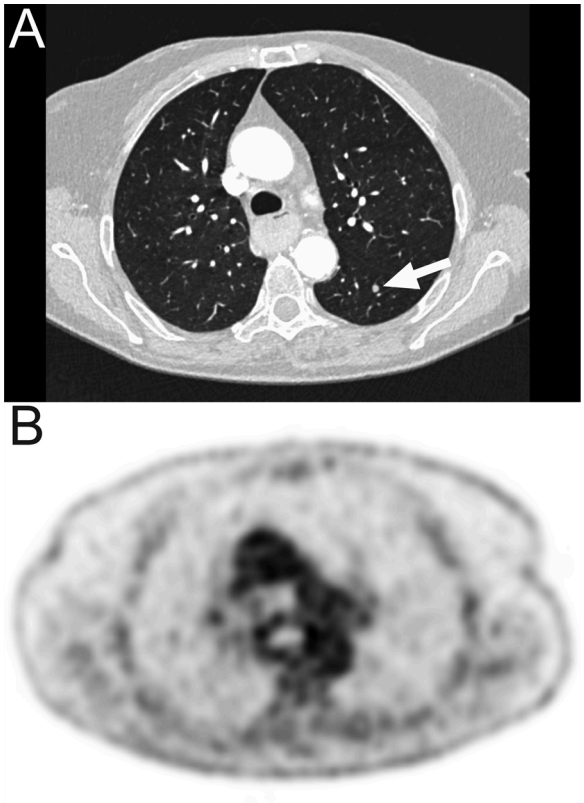

Fig. 7. A 77-year-old woman with a history of colon cancer, oropharyngeal cancer, and recently diagnosed esophageal cancer. Low-dose FDG-PET/CT and concomitant full-dose contrast-enhanced CT were performed for staging purposes. FDG-PET/CT showed pathologic FDG uptake in the esophageal cancer and several FDG-avid locoregional lymph nodes (not shown). Axial CT in lung window settings (A) and FDG-PET (B) are demonstrated. CT shows a 5-mm pulmonary nodule (A, arrow) without any visible FDG uptake at PET (B). This nodule was considered suspicious for metastatic disease in the original report. However, this nodule was also present at CT performed 2 years before. Therefore, it was highly unlikely to represent a lung metastasis. This cognitive error was corrected with an addendum one day after authorization of the original report.

structural information from the diagnostic-quality CT scan that is not visible on FDG-PET and/or satisfaction of search after the initial FDG-PET interpretation. To support this hypothesis, the proportion of perceptual errors was compared between low-dose FDG-PET/CT only and low-dose FDG-PET/CT combined with full-dose contrast-enhanced CT. In addition, the proportions of perceptual errors in the latter group (i.e. low-dose FDG-PET/CT combined with full-dose contrast-enhanced CT) that were due to findings that were visible on CT only, on FDG-PET only, and on both FDG-PET and CT, were calculated.

The post-hoc analysis of all 90 diagnostic errors revealed that, proportion-wise, perceptual errors were more common when low-dose FDG-PET/CT was combined with full-dose contrast-enhanced CT (39/60, 65.0%) than when it was not (15/30, 50.0%). In addition, the majority of perceptual errors in the 39 low-dose FDG-PET/CT scans that were combined with full-dose contrast-enhanced CT, were due to findings that were visible on CT only (22/39, 56.4%), while the remainder was due to findings visible on FDG-PET only (12/39, 31.8%) and findings visible on both FDG-PET and CT (5/39, 12.8%).

4. Discussion

The results of this study show that diagnostic errors in clinical FDG-PET/CT, as identified by addenda to the original report, are relatively infrequent (around 2%) but nevertheless non-negligible. Perceptual

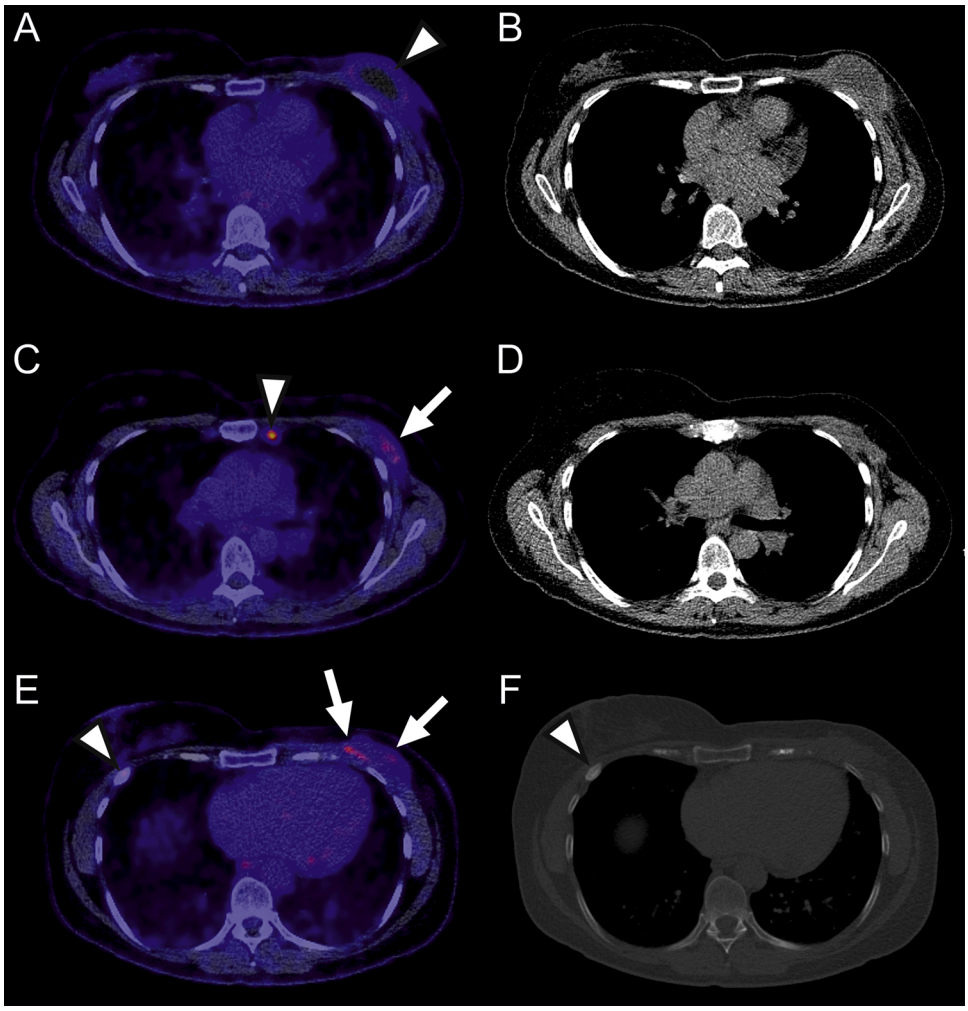

Fig. 8. A 47-year-old woman with a history of breast cancer and mastectomy, and focally increased uptake in several ribs on recently performed bone scintigraphy (not shown). Low-dose FDG-PET/CT was performed to evaluate for metastatic disease. Axial fused FDG-PET/CT (A, C, E) with corresponding low-dose CT (B, D, F) slices at three different levels are demonstrated. FDG-PET showed slight FDG uptake around the breast prosthesis (A, arrowhead), but also high FDG uptake in the soft tissues in the left axilla (C and E, arrows) and in a left internal mammary lymph node (C, arrowhead), and focally increased FDG uptake in a right-sided rib (E, arrowhead), which were interpreted as recurrent metastatic breast cancer in the original report. However, before FDG-PET/CT it was already known that the breast implant was leaking and that there was an inflammatory reaction in the surrounding tissues. This information was available in the patient's clinical records, but not in the request form for FDG-PET. Based on this information, the increased FDG uptake in the soft tissues in the left axilla and in the left internal mammary lymph node were likely attributable to the leaking breast implant. Furthermore, low-dose CT showed callus formation in the right-sided rib with increased FDG uptake (F, arrowhead), suggestive of fracture. Three-year follow-up did not show any signs of metastatic disease. These cognitive errors were corrected with an addendum 7 days after authorization of the original report.

errors outnumbered cognitive errors with a ratio of 60% to 40%. This 60% perceptual error proportion is relatively on the lower end when compared to the previously quoted 60%-80% perceptual error proportion of all diagnostic errors in radiological (non-FDG-PET/CT) examinations [2]. The relatively lower proportion of perceptual errors may be explained by the fact that, overall, FDG-PET/CT is a relatively sensitive imaging modality for the detection of pathology [1]. The relatively higher proportion of cognitive errors for FDG-PET/CT in this study may in part be explained by the fact that FDG is a non-specific radiotracer.

Univariately, the availability of a concomitantly acquired and interpreted full-dose contrast-enhanced CT, and interpretation of FDG-PET/CT by a nuclear medicine physician only, emerged as potentially associated with an increased risk of diagnostic error. Multivariately, only the former remained significantly associated with an increased risk of diagnostic error. Although this finding may appear counterintuitive at a first glance, it can be explained by the fact that a full-dose contrast-enhanced CT scan contains a lot of structural information and potential pathology that may not be visible on low-dose FDG-PET/CT, and can thus be overlooked or misinterpreted. Particularly when relying on FDG-PET information, satisfaction of search bias may arise (i.e. the visual search pattern is discontinued after the interpreting physician has become pleased with the findings observed on FDG-PET) [3]. Due to this satisfaction of search bias, the interpretation of the concomitantly acquired full-dose contrast-enhanced CT scan may become compromised, particularly in terms of more perceptual errors. This hypothesis was supported by a post-hoc analysis that demonstrated the proportion of perceptual errors to be higher (65.0%) when low-dose FDG-PET/CT was combined with full-dose contrast-enhanced CT than when it was not (50.0%). In addition, the majority (56.4%) of perceptual errors in the setting when diagnostic-quality CT scan was concomitantly performed, was due to findings that were visible on CT only. In our department, low-dose FDG-PET/CT is interpreted before full-dose contrast-enhanced CT, and the low-dose FDG-PET/CT scan and the corresponding preliminary report are available for review to the full-dose contrast-enhanced CT reader. This workflow may introduce satisfaction of search errors. Nuclear medicine physicians and radiologists should be conscious of this potential pitfall when reading FDG-PET/CT, and adjust their workflow or mindset accordingly.

Interestingly, in a previous survey study among 663 referring physicians on their experience with the interpretation of oncological FDG-PET/CT studies, perceived misinterpretation rates ranged from 5% to 20%, according to 59.3% of the participants [7]. Overinterpretation rather than underinterpretation was more frequently encountered according to the referring physicians (68.9% vs. 8.7%, respectively) [7]. Limited availability of a patient's history and limited experience of interpreters were the major contributors to this phenomenon, according to 46.8% and 26.7% of the participants in this survey, respectively [7]. Provision of adequate history when ordering an examination and multidisciplinary meetings may indeed reduce diagnostic errors. However, on the basis of the results of the present study, reader experience does not affect diagnostic error rate.

Addenda are made with the purpose to correct or expand on an original radiology report [4], and they can be used as a valuable source to study errors [5]. In a previous study on this topic, 5,568 (0.8 %) of all

Table 3
Results of univariate and multivariate logistic regression analysis on the association between patient, FDG-PET/CT acquisition, and FDG-PET/CT interpretation variables with the presence of a diagnostic error.

Variable	Univariate analysis			Multivariate analysis		
	Odds ratio	95% CI	*P*-value	Odds ratio	95% CI	*P*-value
Patient age	0.99	0.99-1.01	0.48			
Patient gender (male vs. female)	1.15	0.8-1.66	0.45			
Hospital status (in- vs. outpatient)	0.73	0.45-1.16	0.18			
Clinical indication for FDG-PET/CT						
-Oncology vs. others	1.52	0.56-4.17	0.42			
-Infection vs. others	1.32	0.39-4.45	0.65			
-Inflammation vs. others	0.88	0.22-3.58	0.86			
Concomitantly acquired and interpreted full-dose contrast-enhanced CT vs. low-dose FDG-PET/CT acquisition and interpretation only	2.11	1.43-3.10	***<0.001***	2.79	1.61-4.85	***<0.001***
Two vs. one FDG-PET/CT readers[a]	0.96	0.67-1.38	0.83			
Experience first reader[a]	1.01	0.99-1.04	0.29			
Experience second reader[a]	1.02	0.98-1.06	0.44			
FDG-PET/CT read by nuclear medicine physician only vs. FDG-PET/CT scan read by both nuclear medicine physician and radiologist	1.48	0.98-2.24	***0.06***	0.75	0.44-1.27	0.28

Notes:
[a] Only medical imaging specialists (radiologists or nuclear medicine physicians) were counted.

719,855 diagnostic radiology reports that were compiled in a tertiary care center over a 1-year period (June 2013 to May 2014), contained an addendum [5]. In a subanalysis, 228 (26.8 %) of 851 addenda were issued due to perceptual errors [5]. However, the number of cognitive errors was not clearly reported, and no analysis was made on frequency, types and determinants of diagnostic errors for FDG-PET/CT in that study [5]. Other studies on this topic and on diagnostic errors in clinical FDG-PET/CT in general are completely lacking.

The present study had several limitations. First, diagnostic errors extracted from addenda do not yield all diagnostic errors that are made in clinical FDG-PET/CT reading. Therefore, the true number of diagnostic errors is undoubtedly higher. However, peer review of all individual FDG-PET/CT scans for diagnostic errors is challenging, because the definition of "truth" varies, even among experienced radiologists [5, 8]. The use of addenda for analysis of diagnostic errors has been reported to be a more reproducible method [5]. It should be mentioned that the use of addenda may not be a common practice in all countries and institutions. Nevertheless, for imaging departments that already use an addenda system in routine clinical practice, the findings of the present study can be used for benchmarking purposes. Second, several other variables that were not analyzed in the present study, may be associated with diagnostic error rate, such as the availability of adequate clinical information, and previous imaging before FDG-PET/CT.

In conclusion, diagnostic errors in clinical FDG-PET/CT based on addenda to the original report are relatively infrequent, though certainly non-negligible. Perceptual errors are slightly more frequent than cognitive errors. The availability of a concomitantly acquired and interpreted full-dose contrast-enhanced CT seems to increase diagnostic error rate. These data can be used for quality improvement and benchmarking purposes.

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IRB statement

- The institutional review board of the University Medical Center Groningen approved this retrospective study (registered in the UMCG research register with number 201900013) and waived the requirement for written informed consent
- This study has been performed in accordance with the ethical standards in the 1964 Declaration of Helsinki
- This study has been carried out in accordance with relevant regulations of the US Health Insurance Portability and Accountability Act (HIPAA)

CRediT authorship contribution statement

Norah A. Alotaibi: Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing - original draft, Writing - review & editing. **Derya Yakar:** Conceptualization, Investigation, Methodology, Supervision, Visualization, Writing - original draft, Writing - review & editing. **Andor W.J.M. Glaudemans:** Conceptualization, Investigation, Methodology, Supervision, Visualization, Writing - original draft, Writing - review & editing. **Thomas C. Kwee:** Conceptualization, Investigation, Methodology, Supervision, Visualization, Writing - original draft, Writing - review & editing.

Declaration of Competing Interest

The authors reported no declarations of interest.

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